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# Transient X-ray sources in the field of the Unidentified Gamma-Ray Source TeV J2032+4130 in Cygnus

Received: date / Accepted: date

**Abstract** We present an analysis of *Chandra* ACIS observations of the field of TeV J2032+4130, the first unidentified TeV source, detected serendipitously by HEGRA. This deep (48.7 ksec) observation of the field follows up on an earlier 5 ksec *Chandra* director’s discretionary observation. Of the numerous point-like X-ray sources in the field, the brightest are shown to be a mixture of early and late-type stars. We find that several of the X-ray sources are transients, exhibiting rapid increases in count rates by factors 3–10, and similar in nature to the one, hard absorbed transient source located in the earlier *Chandra* observation of the field. None of these transient sources are likely to correspond to the TeV source. Instead, we identify a region of diffuse X-ray emission within the error circle of the TeV source and consider its plausible association.

**Keywords** gamma-rays: individual (3EG J2033+4118, TeV J2032+4130) · gamma-rays: observations · X-rays: stars

## 1 Introduction

TeV J2032+4130 was the first unidentified gamma-ray source detected at TeV energies. The source was discovered serendipitously in the direction of the Cygnus OB2 stellar association region by the HEGRA CT-System at La Palma [1, 2] in observations originally devoted to Cygnus X–3. The HEGRA observations, carried out between 1999 and 2002, found TeV J2032+4130 to be a steady gamma-ray source, with the integrated flux measured above 1 TeV at  $\approx 5\%$  of that of the Crab Nebula. The best fit HEGRA position for the source is  $20^{\text{h}}31^{\text{m}}57^{\text{s}} \pm$

$6^{\text{s}}2_{\text{stat}} \pm 1^{\text{s}}0_{\text{sys}}, +41^{\circ}29'56.8'' \pm 1'.1_{\text{stat}} \pm 1'.0_{\text{sys}}$  (J2000) [3]. The source was reported to be extended, with a Gaussian  $1\sigma$  radius of  $\sim 6'.2 (\pm 1'.2_{\text{stat}} \pm 0'.9_{\text{sys}})$ . TeV J2032+4130 was also detected in the Whipple archival data taken in 1989 and 1990 [4], with some indication that the source may be variable on the time scale of several years. It is interesting to note that the error circle of TeV J2032+4130 overlaps the edge of the 95% confidence error ellipse of an EGRET source, 3EG J2033+4118. However, it is not clear if they are associated.

The field of TeV J2032+4130 was initially observed by *Chandra* during a short 5 ksec exposure [5]. In an attempt to understand the possible origins of the source, we performed a multiwavelength study of the region, carrying out optical identifications and spectroscopic classifications of the bright X-ray sources in the *Chandra* ACIS image and (archival) *ROSAT* PSPC data [6]. The X-ray sources detected were found to be a mix of early- and late- type stars, and there was no compelling counterpart to the gamma-ray source. However, in our study of the *Chandra* ACIS field, we did find an unusual new, hard absorbed source that was both transient and rapidly variable. We reported on the detection of this source (*Chandra* Source 2 in [6]) as the brightest source in the *Chandra* field, located at  $20^{\text{h}}31^{\text{m}}43.755^{\text{s}}, +41^{\circ}35'55.17''$  (J2000), at a distance of  $7'$  from the centroid of the TeV emission. We detected a coincident reddened optical counterpart with the MDM Observatory 2.4m telescope, but without any emission or absorption features in its spectrum. Although the transient source was the brightest of the *Chandra* sources, it was noticeably absent from earlier *ROSAT* or *Einstein* images. At the time of our initial study of this field, we considered the possibility of this transient X-ray source being a candidate for a “proton” blazar [7], a radio-weak gamma-ray source that could be associated with TeV J2032+4130 [6]. However, without knowing the exact nature of this source, we were unable to consider it a compelling counterpart.

Since the original study, a deep 50 ksec *Chandra* observation of the TeV J2032+4130 field has been acquired. An analysis of this data recently summarized in [8] found

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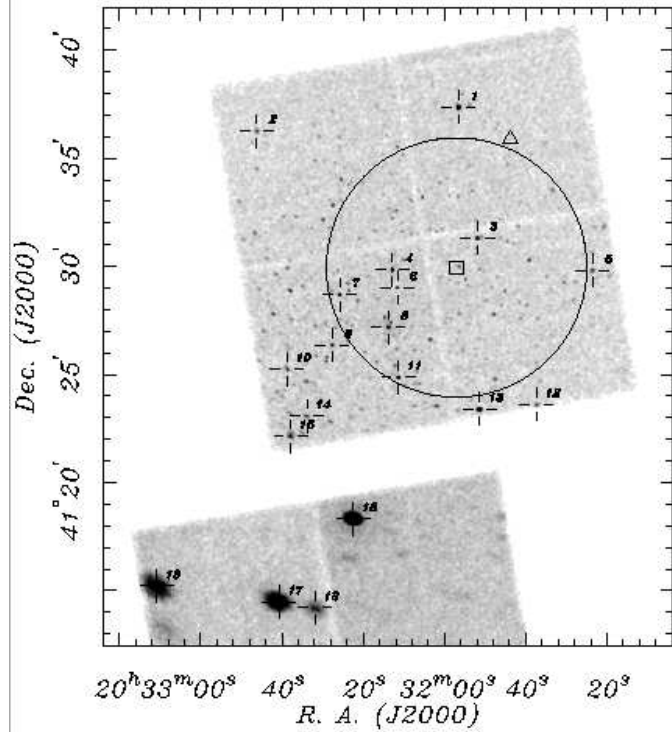
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$\approx 240$  point-like X-ray sources in the *Chandra* field, but no obvious diffuse X-ray counterpart to TeV J2032+4130. We have reanalyzed this new *Chandra* exposure and find that at least seven of the brightest X-ray point sources are either flare stars or transients. The brightest *Chandra* source, “Source 2” from our earlier study is no longer detected. We are now convinced that *Chandra* Source 2 reported in [6] is a flare star, not associated with TeV J2032+4130. In this paper we (a) summarize the properties of the several transient sources discovered in the *Chandra* field of TeV J2032+4130, (b) identify a diffuse candidate X-ray counterpart, and (c) review our conclusions about the possible nature of the gamma-ray source.

## 2 X-ray Observations

On 2004 July 12, *Chandra* acquired a 48.7 ks observation of the field of TeV J2032+4130 with the front-illuminated, imaging CCD array of the Advanced CCD Imaging Spectrometer (ACIS-I). ACIS is sensitive to photons in the energy range 0.2–10 keV with a spectral resolution of  $\Delta E/E \sim 0.1$  at 1 keV. Data reduction and analysis were performed using the standard analysis software packages, CIAO, FTOOLS, and XSPEC. Figure 1 shows the *Chandra* image of the region, with the position of TeV J2032+4130 marked. There are numerous point-like X-ray sources near the centroid of the TeV source: Butt et al. (2006) find 240 point-like X-ray sources in a recent study of the field [8]. We have marked the positions of the brightest point sources, those having at least 100 photons and a signal-to-noise ratio  $5\sigma$  or greater, in Fig. 1. The positions, count rates and hardness ratios of these sources are given in Table 1. A comparison of this field with the earlier 5 ksec *Chandra* exposure [6] shows that several of the point sources from the earlier *Chandra* observation are detected in this deeper exposure. However, it is notable that the brightest X-ray source from the earlier observation is absent from the image shown in Fig. 1. The position of this transient source discovered by [6] is marked in the figure with a triangle.

We find that several of the sources in the *Chandra* field have ordinary stellar counterparts. Many of the stars in the Cyg OB2 association are among the strongest stellar X-ray sources in the Galaxy. Likely optical identifications of the *Chandra* sources are given in Table 1. The magnitudes listed in the table are from the USNO-A2.0 and USNO-B1.0, where available, or from the MT91 [9] compilation of stars in Cyg OB2, or from the optical images obtained by us during our earlier study of this field [6]. Two of the sources have no optical counterparts. Both were detected in the earlier *Chandra* observation, and have no optical counterpart to a limiting magnitude greater than 23 [6]. As in our earlier analysis, we find these to be the hardest sources in the image. They are likely to be active galaxies, highly absorbed by the



**Fig. 1** *Chandra* ACIS-I image of the field of TeV J2032+4130. The positions of the marked sources are given in Table 1. The small square marks the centroid of TeV J2032+4130, and the circle is the estimated Gaussian  $1\sigma$  extent of the TeV emission [3]. The triangle marks the brightest *Chandra* source in an earlier 5 ksec observation of the region [6], noticeably absent from this image.

Galactic ISM, and are unlikely to be nearby, old neutron stars.

## 3 Transient X-ray Sources in the Field of TeV J2032+4130

Seven of the sources in Table 1 were not detected in the earlier *ROSAT* [10] or *Chandra* [6] observations of this field. Thus, they may be described as transient sources. Figure 2 shows the lightcurve of the brightest of these sources (# 4), constructed from the 48.7 ks *Chandra* observation. The aperture of the source and background regions are indicated in the figure. The background is seen to be sufficiently stable and has little effect on the source light curves. The figure shows that the count rate rose by more than a factor of 10 in the final 15 ks of the observation, after remaining faint for the first 35 ks. We see a similar behavior in the case of the other transient sources. We believe that these are flare stars, which commonly exhibit X-ray flaring activity (e.g. [11]).

**Table 1** *Chandra* Sources in the Field of TeV J2032+4130: Likely Counterparts

ID	X-ray Position <sup>a</sup>		Cts <sup>b</sup>	HR <sup>c</sup>	Optical Position <sup>a</sup>		Name	Sp. Type	<i>B</i> mag	<i>R</i> mag
	R.A.	Decl.			R.A.	Decl.				
1	20 31 56.50	+41 37 22.00	808	0.56	.....		...			> 23.2
2	20 32 46.23	+41 36 16.03	445	-0.22	20 32 46.240	+41 36 16.0	MT91 321		11.23	10.28
3	20 31 51.87	+41 31 18.91	206	0.76	.....		...			> 23.7
4	20 32 12.78	+41 29 50.94	843	0.15	20 32 12.763	+41 29 51.24	...			19.2
5	20 31 23.58	+41 29 49.29	274	-0.21	20 31 23.573	+41 29 49.45	...			15.1
6	20 32 11.60	+41 29 01.41	113	-0.05	20 32 11.600	+41 29 01.48	...			15.5
7	20 32 25.78	+41 28 42.28	160	-0.18	20 32 25.731	+41 28 42.89	...			17.3
8	20 32 13.84	+41 27 11.66	290	-0.75	20 32 13.836	+41 27 12.33	Cyg OB2 4	O7 III((f))	11.42	10.2
9	20 32 27.63	+41 26 21.76	179	-0.60	20 32 27.663	+41 26 22.44	MT91 258			10.4
10	20 32 38.72	+41 25 14.75	440	-0.31	20 32 38.580	+41 25 13.6	MT91 299	O7.5V	12.03	
11	20 32 11.32	+41 24 52.02	301	-0.08	20 32 11.303	+41 24 52.69	...			17.0
12	20 31 37.32	+41 23 37.19	232	-0.51	20 31 37.267	+41 23 36.01	MT91 115	G6 V	13.90	13.1
13	20 31 51.30	+41 23 23.44	722	-0.78	20 31 51.319	+41 23 23.79	MT91 152	G3 V	13.40	13.1
14	20 32 33.84	+41 23 04.46	623	0.17	20 32 33.862	+41 23 04.27	...			16.7
15	20 32 37.85	+41 22 08.79	931	0.10	20 32 37.820	+41 22 08.98	...			18.5
16	20 32 22.42	+41 18 18.97	28127	-0.55	20 32 22.425	+41 18 18.96	Cyg OB2 5	O7e	10.64	8.1
17	20 32 40.66	+41 14 28.96	16558	-0.26	20 32 40.959	+41 14 29.29	Cyg OB2 12	B5Iab:	14.41	...
18	20 32 31.85	+41 14 12.15	9440	-0.13	20 32 31.556	+41 14 08.48	MT91 267	...	15.06	11.8
19	20 33 10.83	+41 15 12.56	14479	-0.28	20 33 10.736	+41 15 08.22	Cyg OB2 9	O5Iab:e	12.61	...

(a) Units of right ascension are hours, minutes, and seconds. Units of declination are degrees, arcminutes, and arcseconds.

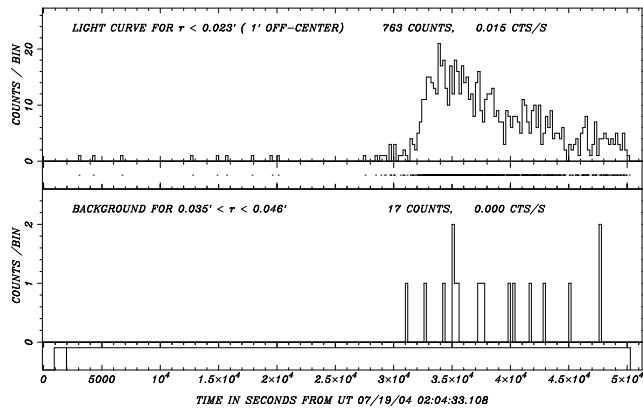
(b) Total counts in a 12'' radius aperture. The total included background is estimated as 1–3 counts. (c) Hardness ratio (HR) is defined as:  $\frac{S(0.5-2\text{keV}) - S(2-10\text{keV})}{S(0.5-2\text{keV}) + S(2-10\text{keV})}$ , where  $S$  is the source counts in a given energy band.

In comparison, the only transient source in our earlier *Chandra* field was also highly variable during the brief 5 ks observation. It remained faint for the first 3.5 ks, but increased its count rate by ten-fold in the final 1.5 ks. This source is not detected in the deep *Chandra* observation of the field.

Flare stars are generally dim, red (class-M) dwarfs that are seen to exhibit unusually violent activity in optical and/or X-ray bands, and sometimes in the radio

and ultraviolet bands. Flare stars are not known to be gamma-ray emitters. It is unlikely that any of the transient X-ray sources are point source counterparts to TeV J2032+4130.

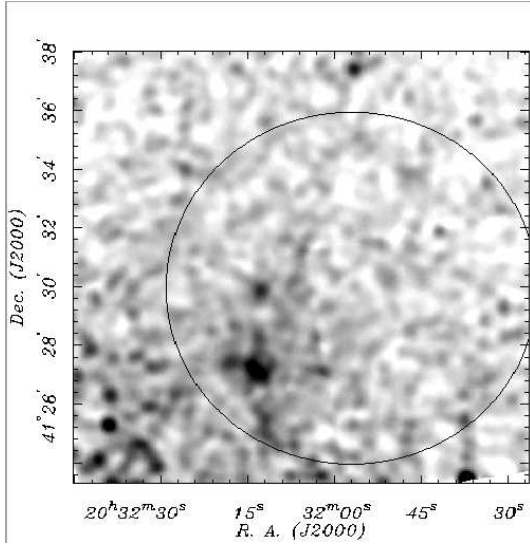
One of the suggestions for the origin of an extended region of TeV emission, as in the case of TeV J2032+4130, is inverse Compton scattering from a jet-driven termination shock from Cyg X-3 or an as yet undetected microquasar [1]. In [6] we were motivated to further study the one transient source in the field in order to investigate if it could be such a jet source. Based on the new *Chandra* observation and the detection of several similar transient sources, it is clear that the one transient source in [6] is not a microquasar, or responsible for the TeV emission in any way.



**Fig. 2** Lightcurves (top) and local background (bottom) of *Chandra* source 4 (Table 1). The aperture sizes for the source extraction and background regions are indicated in the figure. A time binning of 200 s was used. The dots below the light curve are the arrival times of the individual photons. The background is demonstrated to be stable and has negligible effect on the source light curve.

#### 4 Diffuse X-ray Emission in the Field of TeV J2032+4130

We carried out an analysis to search for diffuse, extended X-ray emission in the TeV source region. Figure 3 shows an image of the diffuse emission only, made by locating and cutting out the point sources, and smoothing the resulting image with a Gaussian kernel of sigma 14''. This image is exposure and vignetting corrected in the broad energy band of 0.3 to 8 keV. The extended emission centered on 20<sup>h</sup>32<sup>m</sup>13.4<sup>s</sup>, +41°27'10.4'' (J2000) is detected at a significance of 6.1 $\sigma$ , and has an extent of roughly  $\sim 1.6'$  diameter, with a few features extending further. It is possibly associated with Cyg OB2 #4. For



**Fig. 3** *Chandra* ACIS-I image of the field of TeV J2032+4130 showing diffuse emission only in the 0.3-8 keV band. The image has been exposure and vignetting corrected. The circle is the estimated Gaussian  $1\sigma$  extent of the TeV emission [3].

the circular aperture of  $1.6'$  diameter, the diffuse X-ray flux is  $8 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$  in the 0.5–10 keV band, assuming a power-law spectral model with photon index of 1.5, typical of non-thermal spectra and total Galactic  $N_H = 1.5 \times 10^{22} \text{ cm}^{-2}$ . By comparing the exposure and vignetting corrected images of the region in the soft and hard energy bands of 0.3–2.0 keV and 2.0–8.0 keV, respectively, we find no significant softening of the spectrum in the high energy band. The corresponding hardness ratio is  $-0.48$ .

## 5 Discussion and Conclusions

Based on the deep *Chandra* observations of the TeV field, we summarize our principal findings as follows.

We find several new transient sources in the *Chandra* field of TeV J2032+4130. These are similar in nature to the one transient source found in the earlier 5 ks *Chandra* observation of the field. We are convinced that these transient sources are flare stars, unlikely to be associated with the TeV source.

Mukherjee et al. (2003) [6] considered the candidacy of the one transient source detected in the field of TeV J2032+4130 for either a “proton blazar” or a jet source responsible for TeV emission via inverse Compton scattering. Based on the new data, we are convinced that this is not the case.

We find no convincing point source counterpart to TeV J2032+4130 in the X-ray band.

We find significant hard diffuse X-ray emission within the error circle of TeV J2032+4130. If the source of the diffuse emission is embedded in the Cygnus OB2 associ-

ation at  $d = 1740 \text{ pc}$  [9], the corresponding luminosity is  $\sim 3 \times 10^{31} \text{ erg s}^{-1}$ .

TeV J2032+4130 appears to be an extended source, unlikely to have a point source counterpart at other wavelengths. It seems to be related to the massive Cyg OB2 association and the massive stars in the region. Aharonian et al. (2002) [1] discuss two possible origins of the extended TeV emission from the source. The emission could be hadronic in origin, arising from the acceleration of hadrons in shocked OB star winds and interaction with local, dense gas cloud, and subsequent  $\pi^0$  decay. Or, the TeV emission could be inverse Compton scattering in a jet-driven termination shock from Cyg X-3 or an as yet undetected microquasar.

In a recent study, Butt et al. (2006) [8] find that a surface density plot of the point-like X-ray sources in the *Chandra* field shows an excess consistent with the size and position of TeV J2032+4130. One proposal made by these authors is that the TeV source is a composite of several point sources, and it is possible that several of point X-ray sources are responsible for the TeV emission.

The fact that we detect hard X-ray emission within the error circle of TeV J2032+4130 is quite interesting. Together with the TeV observations, it points to the fact that high energy particles are being accelerated in the stellar winds associated with the massive stars in the region. It is not obvious, however, that the diffuse emission is related to the TeV source. We need deeper observations of the region in order to derive an X-ray spectrum of the diffuse emission. It would also be important to see if future observations (with better angular resolution) of TeV J2032+4130 with VERITAS or MAGIC indicate any spatial correlation between the gamma-ray and X-ray emissions. Further observations at TeV energies with ground-based atmospheric Cherenkov telescopes as well as space-based experiments like GLAST are needed to help us resolve the nature of this source.

**Acknowledgements** This publication makes use of data obtained from HEASARC at Goddard Space Flight Center and the SIMBAD astronomical database. R. M. acknowledges support from NSF grant PHY-0244809.

## References

1. Aharonian, F., et al. 2002a, A&A, 393, L37.
2. Rowell, G. & Horns, D. 2002, in The Gamma-Ray Universe, ed. A. Goldwurm, D. Neumann, & J. Tran Thanh Van (Hanoi: Gioi Publ.), 385.
3. Aharonian, F., et al. 2005, A&A, 431, 197.
4. Lang, M. J., et al. 2004, A&A, 423, 415.
5. Butt, Y., et al. 2003, ApJ, 597, 494.
6. Mukherjee, R., Halpern, J. P., Gotthelf, E. V. et al. 2003, ApJ, 589, 487.
7. Mannheim, K. 1993, A&A, 269, 67.
8. Butt, Y., et al. 2006, ApJ, 643, 238.
9. Massey, P., & Thompson, A. B. 1991, AJ, 101, 1408.
10. Waldron, W. L., et al. 1998, ApJS, 118, 217.
11. Haisch, B. M., et al. 1983, ApJ, 267, 280.